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EVALUATION OF A LASER EQUIPPED RIFLE FOR THE US ARMY HUMAN ENGI--ETC(U)
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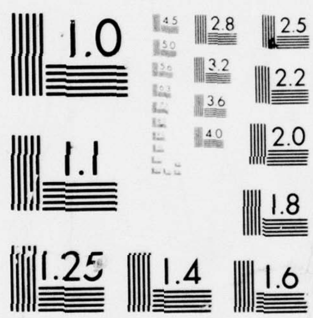

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NONIONIZING RADIATION PROTECTION SPECIAL STUDY NO. 42-0325-77
EVALUATION OF A LASER EQUIPPED RIFLE FOR THE
US ARMY HUMAN ENGINEERING LABORATORY
ABERDEEN PROVING GROUND, MARYLAND
JANUARY 1977

SERVING THE ARMY IN ITS PREVENTIVE MEDICINE PROGRAM

SENTINEL OF HEALTH

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A special study of the optical radiation hazards associated with the operation of a He-Ne laser mounted to an American International Corporation Model 180 Law Enforcement Rifle was performed by this Agency. Radiometric measurements were conducted on 11 January 1977, for the US Army Human Engineering Laboratory at Aberdeen Proving Ground. It was determined that the protection standards for momentary viewing were exceeded out to a hazard distance of 9 m and to 100 m when viewing through an optical instrument. Long-term staring

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DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

28 MAR 1977

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ABSTRACT

A special study of the optical radiation hazards associated with the operation of a He-Ne laser mounted to an American International Corporation Model 180 Law Enforcement Rifle was performed by this Agency. Radiometric measurements were conducted on 11 January 1977, for the US Army Human Engineering Laboratory at Aberdeen Proving Ground. It was determined that the protection standards for momentary viewing were exceeded out to a hazard distance of 9 m and to 100 m when viewing through an optical instrument. Long-term staring at the laser from within the beam exceeded the protection standards out to a caution distance of 490 m.

It is recommended that: the laser not be pointed at the unprotected eyes of personnel within the hazard distance, unprotected personnel not be allowed to continuously stare into the beam within the caution distance, the laser not be pointed toward nearby flat mirror surfaces, and an appropriate warning label be affixed to the device. It is further recommended that the laser output power be reduced below 1 mW, if feasible, to eliminate a potential hazard for retinal injury from momentary viewing.

DEPARTMENT OF THE ARMY
U. S. ARMY ENVIRONMENTAL HYGIENE AGENCY
ABERDEEN PROVING GROUND, MARYLAND 21010

HSE-RL/WP

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1. AUTHORITY.

a. AR 40-5, Health and Environment, 25 September 1974.

b. Letter, DRXHE-SP, US Army Human Engineering Laboratory, Aberdeen Proving Ground, 30 December 1976, subject: Laser Safety for Test of a Laser Equipped Rifle.

2. REFERENCES.

a. Paragraph 2-35a(7), AR 10-5, Department of the Army, 1 April 1975.

b. AR 40-46, Control of Health Hazards from Lasers and Other High Intensity Optical Sources, 6 February 1974.

c. TB MED 279, Control of Hazards to Health from Laser Radiation, 30 May 1975.

d. Title 21, Code of Federal Regulations (CFR), 1976 ed., Part 1040, Performance Standards for Light-Emitting Products.

3. PURPOSE. To evaluate potential health hazards associated with the use of a laser equipped rifle and to make recommendations designed to eliminate exposure of personnel to potentially hazardous radiation from this device.

4. GENERAL.

a. Background. This Agency was requested to evaluate a Spectra-Physics laser mounted on an American International Corporation 180 law enforcement rifle by the US Army Human Engineering Laboratory for feasibility for combat simulation field tests at Aberdeen Proving Ground. The laser system is illustrated in Figure 1. The system was manufactured by American International Corporation, Salt Lake City, Utah. The battery operated laser is employed as a line-of-sight aiming device for the rifle and serves normally as a deterent to criminals confronted by law enforcement officers. The laser spot indicates the point of impact for the rapid-fire, small-caliber rifle.

FIGURE 1. American International Corporation 180 Law Enforcement Rifle with *SC 200 Laser Lok Sight* Mounted Below Rifle Barrel

b. Inventory. At the time of this study the US Army Human Engineering Laboratory had one He-Ne laser on hand.

c. Instrumentation.

(1) United Detector Technology Model 40X Optometer with Radiometric Filter.

(2) Calibrated Neutral Density Filters.

d. Abbreviations. A table of radiometric terms and units is provided in Appendix A.

5. FINDINGS.

a. Laser Output Parameters. The following laser output parameters were determined:

(1) Wavelength: 632.8 nm (He-Ne laser wavelength).

(2) Radiant Power: 3.1 mW measured, 2 mW specified.

(3) Effective Emergent Beam Diameter: Circular beam with an approximate diameter of 0.5 mm.

(4) Effective Beam Divergence: 1.3 mrad divergence at 1/e-peak-irradiance-points measured, 1.6 mrad specified.

(5) Hazard Classification: Class IIIb medium power laser.

b. Beam Characteristics as a Function of Range. Radiometric measurements of beam irradiance versus range were made on 11 January 1977 at Aberdeen Proving Ground. A power meter with a 1-cm diameter circular entrance aperture was placed within the most intense portion of the beam at several distances out to 27 m. The data were corrected to provide the irradiance through a 7-mm and an 80-mm aperture to depict the largest pupillary diameter and telescopic viewing. Results of the corrected data appear in Figure 2. Using Equation 12 of Appendix B and a programmable calculator/plotter, an effective beam divergence of 1.3 mrad was derived.

c. System Safety. The laser device did not incorporate safety features as prescribed in 21 CFR 1040. Such features include an interlocked protective housing, remote control connector, key control, laser radiation emission indicator, beam attenuator and warning labels. Class IIIb laser systems manufactured after 1 August 1976, except prototypes, are required to incorporate such safety features unless an exemption is obtained from the regulation. Future production systems would be required to meet the regulation.

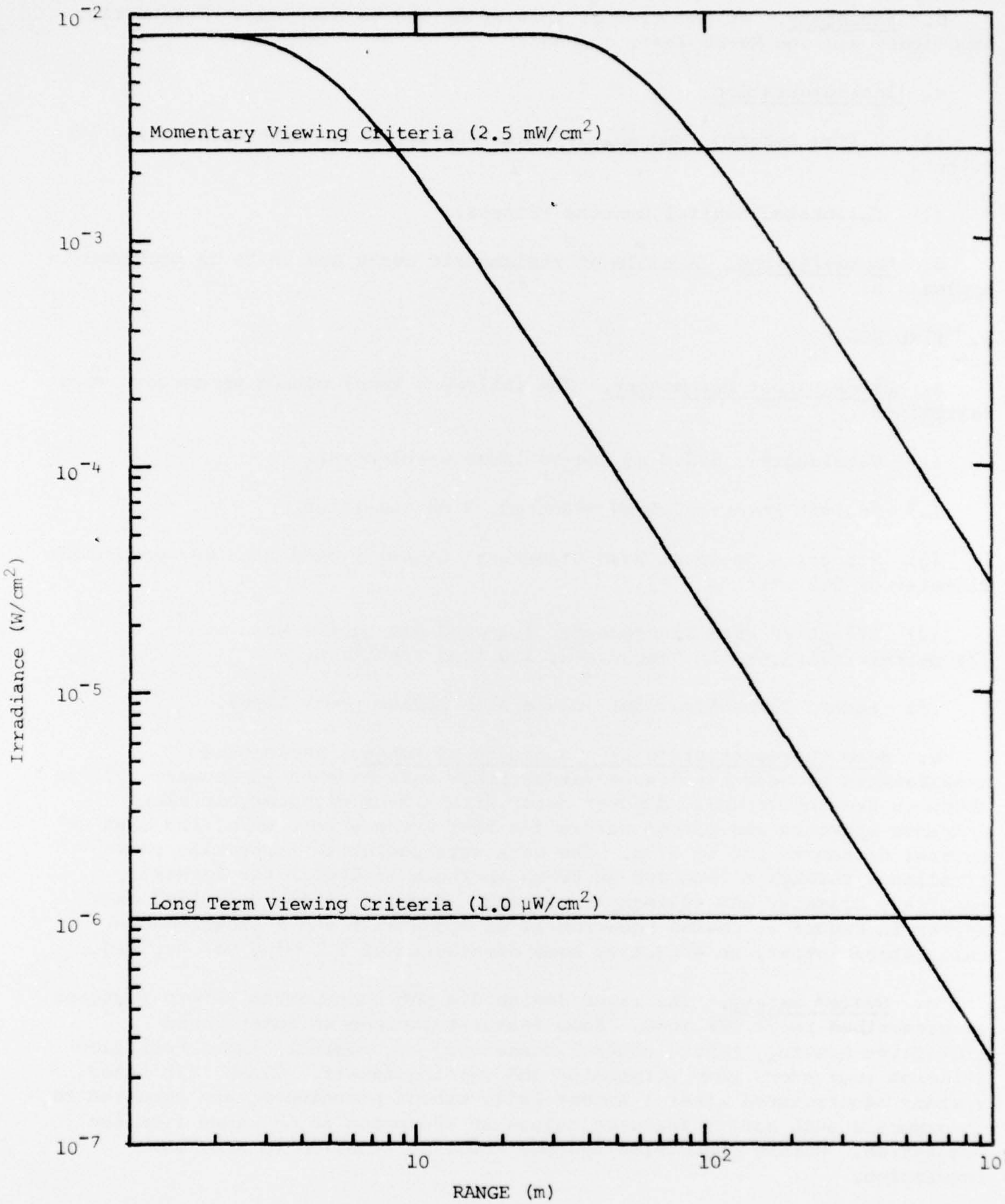

FIGURE 2. Theoretical Beam Irradiance Versus Range for the Laser Equipped Rifle. Lower curve provides irradiance through a 7-mm circular aperture. Upper curve is for an 80-mm aperture. An atmospheric attentuation coefficient of $10^{-7}cm^{-1}$ was assumed.

6. DISCUSSION.

a. Hazard Analysis. The potential hazard from the He-Ne laser is limited to the unprotected eyes of individuals looking at the laser from within the laser beam at close range. The protection standards for a continuous point source laser depend upon the emission wavelength (632.8 nm) and the viewing duration. Momentary viewing, which is limited to the duration of the eye's natural aversion response and blink reflex (0.25 s), allows an exposure up to 2.5 mW/cm^2 averaged over a 7-mm pupillary diameter (worst-case, dark-adapted eye). The standard for long-term (10,000 s to 8 hrs) staring into the beam is 1 $\mu W/cm^2$ through a 7-mm aperture. Comparing these protection standards to the beam irradiance in Figure 2 indicates a hazard distance of 9 m for unaided viewing and 100 m when viewing through an optical instrument with an 80-mm objective lens. Purposeful staring into the beam for long periods exceeds the protection standard out to a caution distance of 490 m.

b. Range Controls. The laser presents a line-of-sight hazard out to the aforementioned hazard distances when the laser beam is pointed toward the unprotected eyes of personnel. Since the hazard does not extend beyond the limit of the operator's vision, the simplest control measure would be to turn off the laser should personnel enter the area of the beam path within the potentially hazardous ranges. Ideally, a backstop should be utilized to terminate the beam within the controlled area. The backstop should present a large angular subtense (~20 mrad) from the operator's position (2 m x 2 m at 100 m). Although glass surfaces placed within the beam path do not reflect sufficient irradiances (only 8 percent) to present a momentary viewing hazard to individuals looking into the reflected beam, mirrored surfaces can. Therefore, it is normal practice to avoid pointing the laser at such surfaces or to remove them from the vicinity of the beam path.

7. CONCLUSION. The laser equipped rifle emits optical radiation exceeding current protection standards. However, this device does not pose a significant hazard provided that the operators are informed of the potential hazards and take appropriate precautions.

8. RECOMMENDATIONS.

a. Do not point the laser at the unprotected eyes of individuals located at distances less than 9 m, or less than 100 m when they are viewing through optical instruments (paragraph 1-4d, AR 40-46).

b. Do not permit continuous staring into the beam within 490 m (paragraph 1-4d, AR 40-46).

c. Do not point the laser at flat specular ("mirrored") surfaces within 4.5 m (paragraph 1-4d, AR 40-46).

d. Install a warning label on the laser which reads as follows: [paragraph 1-5d(1), AR 40-46].

e. Reduce the output power of the laser to below 1 mW, if possible, to eliminate the potential hazard from retinal injury for momentary viewing should several of these devices enter the US Army inventory for law enforcement purposes or two-sided tactical exercises. If this power reduction is not feasible, the emergent beam should be expanded to limit the power passing through a 7-mm aperture to 1 mW (paragraph 1-4d, AR 40-46).

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APPENDIX A

USEFUL CIE RADIOMETRIC AND PHOTOMETRIC TERMS AND UNITS[1,2]

RADIOMETRIC				PHOTOMETRIC			
Term	Symbol	Defining Equation	SI Unit and Abbreviation	Term	Symbol	Defining Equation	SI Units and Abbreviation
Radiant Energy	Q_e		Joule (J)	Quantity of Light	Q_v	$Q_v = \int \Phi_v dt$	lumen-second (lm·s) (talbot)
Radiant Energy Density	W_e	$W_e = \frac{dQ_e}{dV}$	Joule per cubic meter ($J \cdot m^{-3}$)	Luminous Energy Density	W_v	$W_v = \frac{dQ_v}{dV}$	talbot per square meter ($lm \cdot s \cdot m^{-3}$)
Radiant Power (Radiant Flux)	Φ_e, P	$\Phi_e = \frac{dQ_e}{dt}$	Watt (W)	Luminous Flux	Φ_v	$\Phi_v = 680 \int \frac{d\Phi_e}{d\lambda} V(\lambda)\, d\lambda$	lumen (lm)
Radiant Exitance	M_e	$M_e = \frac{d\Phi_e}{dA} = \int L_e \cdot \cos\theta \cdot d\Omega$	Watt per square meter ($W \cdot m^{-2}$)	Luminous Exitance	M_v	$M_v = \frac{d\Phi_v}{dA} = \int L_v \cdot \cos\theta \cdot d\Omega$	lumen per square meter $lm \cdot m^{-2}$
Irradiance or Radiant Flux Density (Dose Rate in Photobiology)	E_e	$E_e = \frac{d\Phi_e}{dA}$	Watt per square meter ($W \cdot m^{-2}$)	Illuminance (luminous flux density)	E_v	$E_v = \frac{d\Phi_v}{dA}$	lumen per square meter ($lm \cdot m^{-2}$) lux (lx)
Radiant Intensity	I_e	$I_e = \frac{d\Phi_e}{d\Omega}$	Watt per steradian ($W \cdot sr^{-1}$)	Luminous Intensity (candlepower)	I_v	$I_v = \frac{d\Phi_v}{dr}$	lumen per steradian (lm·sr) or candela (cd)
Radiance	L_e	$L_e = \frac{d^2\Phi_e}{d\Omega \cdot dA \cdot \cos\theta}$ [5]	Watt per steradian and per square meter ($W \cdot sr^{-1} \cdot m^{-2}$)	Luminance	L_v	$L_v = \frac{d^2\Phi_e}{dr \cdot dA \cdot \cos\theta}$ [5]	candela per square meter ($cd \cdot m^{-1}$)
Radiant Exposure (Dose, in Photobiology)	H_e	$H_e = \frac{dQ_e}{dA}$	Joule per square meter ($J \cdot m^{-2}$)	Light Exposure	H_v	$H_v = \frac{dQ_v}{dA} = \int E_v dt$	lux-second (lx·s)
				Luminous Efficacy (of radiation)	K	$K = \frac{\Phi_v}{\Phi_e}$	lumen per watt ($lm \cdot W^{-1}$)
				Luminous Efficiency (of a broad band radiation)	V(*)	$V(*) = \frac{K}{K_m} = \frac{K}{680}$	unitless
Radiant Efficiency [3] (of a source)	η_e	$\eta_e = \frac{P}{P_i}$	unitless	Luminous Efficacy[3] (of a source)	η_v	$\eta_v = \frac{\Phi_v}{P_i}$	lumen per watt ($lm \cdot W^{-1}$)
Optical Density [4]	D_e	$D_e = -\log_{10} \tau_e$	unitless	Optical Density[4]	D_v	$D_v = -\log_{10} \tau_v$	unitless
				Retinal Illuminance in Trolands	E_t	$E_t = \frac{L_v}{S_p}$	troland (td) = luminance in $cd \cdot m^{-2}$ times pupil area in mm^2

1. The units may be altered to refer to narrow spectral bands in which case the term is preceded by the word *spectral*, and the unit is then per wavelength interval and the symbol has a subscript λ. For example, spectral irradiance H_λ has units of $W \cdot m^{-2} \cdot m^{-1}$ or more often, $W \cdot cm^{-2} \cdot nm^{-1}$.

2. While the meter is the preferred unit of length, the centimeter is still the most commonly used unit of length for many of the above terms and the nm or μm are most commonly used to express wavelength.

3. P_i is electrical input power in watts.

4. τ is the transmission

5. At the source $L = \frac{dI}{dA \cdot \cos\theta}$ and at a receptor $L = \frac{dE}{d\Omega}$

APPENDIX B

DETERMINING A LASER BEAM DIAMETER AND DIVERGENCE TO EVALUATE POTENTIAL RADIATION HAZARDS

1. BACKGROUND. To assess potential health hazards to individuals from exposure to laser radiation requires an understanding of several topics:

a. The shape or profile of the laser beam intensity distribution.

b. How this profile changes as the beam traverses the atmosphere.

c. The defining aperture for the optical radiation protection standards.

2. GAUSSIAN BEAM. The beam profile at a fixed distance from a single-mode laser (often the case for gas lasers) closely resembles a Gaussian distribution. We can express this distribution mathematically for beam irradiance $E(r)$ as a function of radial distance r from the center axis of the beam by:

$$E(r) = E_o e^{-r^2/2\sigma^2} \tag{1}$$

where E_o is the peak irradiance and σ is a constant which is related to the width of the distribution. Normally, the radiant exposure beam profile at the exit of a solid-state pulsed ruby laser system such as from some laser rangefinders does not even remotely follow a Gaussian distribution. At great distances from the laser, however, the beam is "truncated" and broken up into various hot spots. This change in the shape of the beam occurs due to diffraction at the lasers projection optics as well as interactions between the beam and the atmosphere. Measurements of maximal beam irradiance at several points downrange permit the calculation of an effective beam diameter which can be related to σ. Hence, the mathematics of equation 1 could also be used for a pulsed laser system with beam radiant exposure $H(r)$ as a function of radial distance assuming an effective value for σ.

3. BEAM DIAMETER. The diameter of a laser beam is not directly apparent for a Gaussian distribution as opposed to a rectangular beam profile as shown in Figure 1. Laser technologists have defined the beam diameter in different ways. We wish to define the beam diameter such that the peak irradiance can be readily calculated. Consider the total power contained within a beam with radial symmetry. This total power, Φ, is given by the following integral:

$$\Phi = \int_o^\infty E(r)\ 2\pi r\ dr \tag{2}$$

where $2\pi r\ dr$ is the differential area of an infinite diameter circular aperture thru which the beam passes. Combining equations 1 and 2 and integrating we obtain:

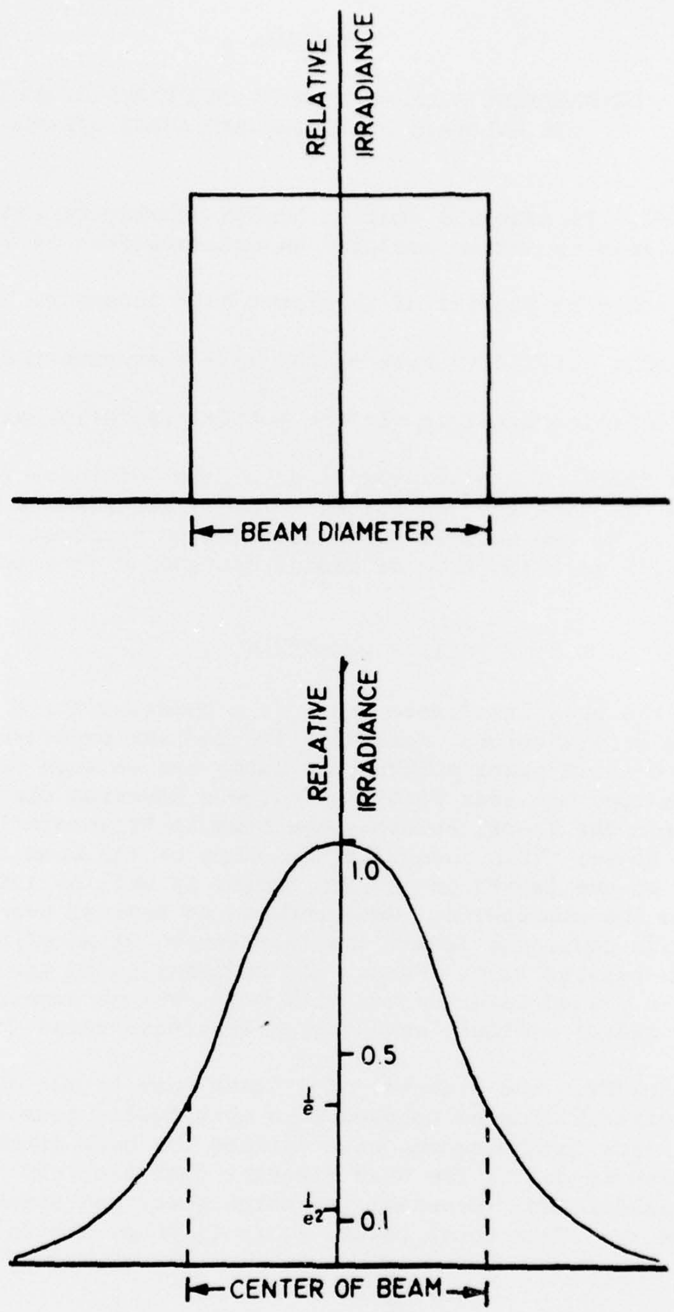

Figure 1. A Gaussian Beam as Illustrated in the Lower Graph has no Clearly Defined Edge as does the Rectangular Beam Profile Illustrated in the Upper Graph.

$$\Phi = \pi D_L^2 E_o/4 \text{ where } D_L \equiv 2\sqrt{2}\sigma \tag{3}$$

Physically D_L defines twice the radial distance to where the irradiance on the Gaussian distribution is reduced to E_o/e (or beam diameter to 1/e-peak-irradiance-points). Therefore by knowing the beam diameter defined at 1/e-peak-irradiance-points and the total power contained within the Gaussian profile it is possible to predict the peak irradiance with the same computation as for a rectangular beam. One simple method for experimentally measuring the beam diameter consists of allowing 63 percent or 1 - 1/e of the total beam power to pass thru an adjustable circular aperture located on the beam axis. The diameter of this aperture is D_L. (This can be mathematically verified by integrating equation 2 to the beam radius at 1/e-peak-irradiance-points or $r = \sqrt{2}\,\sigma$). Figure 2 is a plot of this integral over various limits of integration.

4. BEAM DIVERGENCE. The profile of this laser beam at any other point along its path will also be approximately Gaussian (assuming that other optical systems are not present which might obstruct the path or in any way modify the beam shape). The Gaussian beam in the far field will widen and the peak irradiance will be reduced as we travel farther from the laser. The total power within the beam will be reduced only slightly due to atmospheric absorption. The beam diameter at some distance, r, from the laser is given by:

$$D_L = r \tan \phi + a \tag{4}$$

where ϕ is the beam divergence and a is the diameter to 1/e peak-irradiance-points at the laser output. Since most laser systems are highly collimated we obtain from equation 4:

$$D_L \simeq r\phi + a \tag{5}$$

From this expression it is apparent that the beam divergence must also be specified to 1/e-peak-irradiance-points. To demonstrate this consider specifying the beam diameter to $1/e^2$-peak-irradiance-points (D^1) then from equation 1 we can prove that:

$$D_L = D^1/\sqrt{2} \tag{6}$$

and equivalently:

$$a = a^1/\sqrt{2} \tag{7}$$

Therefore we find that:

$$\phi = \phi^1/\sqrt{2} \tag{8}$$

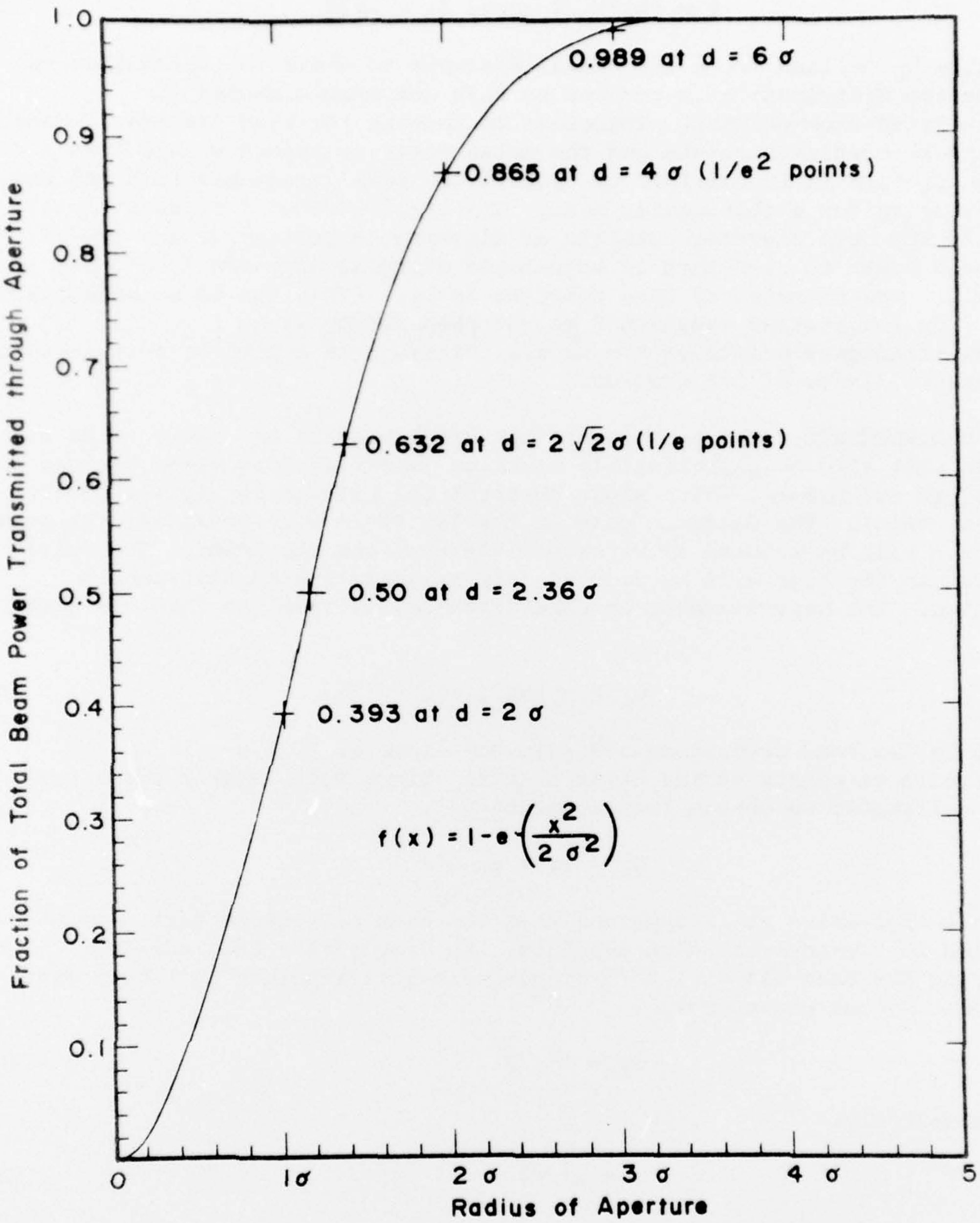

Figure 2. *Beam Diameter is Determined by Measuring the Fraction of Total* Power in a Gaussian Laser Beam which Passes through a Calibrated Aperture. If 63 Percent of the Beam Passes through an Aperture of Diameter, d, then d is the Diameter at 1/e Points. The Diameter at 1/e Points is 1.2 Times the Aperture that Passes 50 Percent of the Total Beam Power.

where a^1 and ϕ^1 are the exit beam diameter and divergence respectively defined to $1/e^2$-peak-irradiance.

The laser range equation is obtained by combining equations 3 and 5 or:

$$E(r) = (1.27\ \Phi\ e^{-\mu r})/(a + r\phi)^2 \qquad (9)$$

where $e^{-\mu r}$ is the atmospheric transmission. (μ is called the atmospheric attenuation coefficient and is normally very small.) Hence, although beam divergence could be defined in several ways, it is convenient for a hazard evaluation to select the beam divergence defined at 1/e-peak-irradiance-points so that it is possible to predict the peak irradiance within a Gaussian profile at any distance from a laser of known output power. We can also apply this equation to experimentally measure the beam divergence. We can measure the peak irradiance with a detector whose sensitive diameter is much smaller than D_L for the beam in the far field of the laser ($r\phi >> a$) and them compute ϕ from equation 9 since Φ, μ, r and a can also be measured.

5. PROTECTION STANDARDS. Why does one need to calculate the peak irradiance in the beam? We do not always need the peak irradiance but normally the beam diameter, D_L, is much larger than the sampling diameter for the laser protection standards since the potential hazard often extends to great distances from the laser. The protection standards for the skin and cornea and lens of the eye are based upon power or energy transmitted through a 1-mm aperture (for wavelengths between 10^5 and 10^6 nm this aperture becomes 10 mm) whereas the aperture for the "retinal hazard region" of the spectrum (400 to 1400 nm) is based upon a 7-mm aperture (dark adapted pupilary diameter). Actual range measurements are performed on laser systems with small exit beam diameters using an appropriate diameter aperture placed directly in front of the detector and centered on the beam axis.

6. RELATIVE BEAM POWER OR ENERGY. The maximum power or energy available to pass thru the appropriate defining aperture (for the various protection standards) is the most useful parameter to determine from the standpoint of evaluating optical radiation hazards. Figure 2 can be used to relate the fraction of total power transmitted thru different diameter apertures when the total beam power is known. Expressed mathematically Figure 2 simply states that the power thru an arbitrary axial aperture of diameter d is:

$$\Phi d = \Phi(1-\beta) \qquad (10)$$

where $\beta = E(d/2)/E_o$ and $d = 2\sigma\sqrt{2\ell n(1/\beta)}$.

By integrating the Gaussian profile over the area of an arbitrary circular aperture and combining this power with equation 3 we obtain another useful expression:

$$\Phi d = \Phi[1-e^{(d/D_L)^2}] \tag{11}$$

Hence a general laser range equation can be seen from equation 11 which could be applied to laser systems which have relatively short retinal hazardous ranges (D_L is of the same order of magnitude as 7 mm) or to telescopic viewing of such beams. The average irradiance over an arbitrary axial circular aperture of diameter d is given by:

$$E(r,d) = 2.6\Phi[1-e^{(d/D_L)^2}]e^{-\mu r} \tag{12}$$

This range equation is primarily applied to low power Ga-As laser diodes and He-Ne lasers.

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